Modelling Nonlinear Site Effects in Physics-Based Ground Motion Simulation

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1. Background

This study examines the performance of nonlinear total-stress wave-propagation site response analysis for modelling site effects in physics-based ground motion simulations of the 2010-2011 Canterbury, New Zealand earthquake sequence. This approach allows for explicit modeling of 3-dimensional ground motion phenomena at the regional scale, as well as detailed site effects and soil nonlinearity at the local scale. The approach is compared to a more commonly used empirical V_{S30} (30 m time-averaged shear wave velocity)-based method for computing site amplification as proposed by Graves and Pitarka (2010, 2015).

2. Site Response Analysis Methodologies

Empirical V_{S30}-Based Method: Figure 1a shows period-dependent nonlinear site amplification factors from the empirical ground motion model (GMM) by Campbell and Bozorgnia (2014). This function is then truncated, as recommended by Graves and Pitarka (2010), for two different reasons: 1) long periods are truncated because the 3D long period component of the simulation should account for deep site response which would influence very long periods, and 2) short periods are truncated because this amplification function is meant to be applied to response spectra, but in this context it is applied to Fourier spectra in the frequency domain.

Physics-Based Wave Propagation Analysis: Figure 1b illustrates physics-based site response via wave propagation, in which simulated ground motions are extracted from the 3D model, deconvolved, and used as input to a nonlinear 1D site response analysis in OpenSees. Because the simulations are viscoelastic, they can be deconvolved in the frequency domain using a transfer function for damped soil over an elastic halfspace.

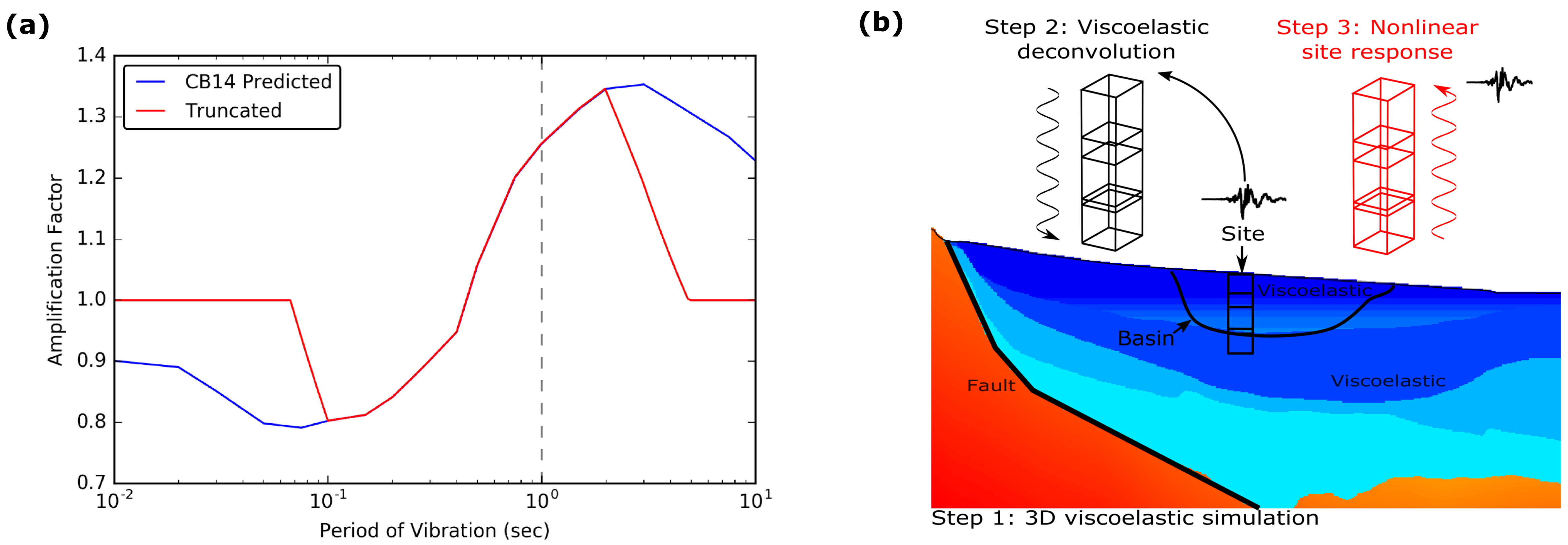

Figure 1: Two methods compared in this study for modelling nonlinear site effects: (a) Empirical V_{S30}-based nonlinear site amplification factors from Campbell and Bozorgnia (2014) GMM, applied to simulated ground motions in the frequency domain, and (b) Simulated ground motions extracted from 3D model, deconvolved, and input to OpenSees for wave-propagation site response analysis.

3. Sites and Earthquakes Considered

Ten events from the 2010-2011 Canterbury earthquake sequence with Mw>4.8 were simulated by Razafindrakoto et al (2016). A detailed wave propagation site response analysis was performed at 16 strong motion stations in Christchurch using these simulations as input. Figure 2 shows the rupture models for all events and the locations of strong motion stations relative to the Christchurch urban area.

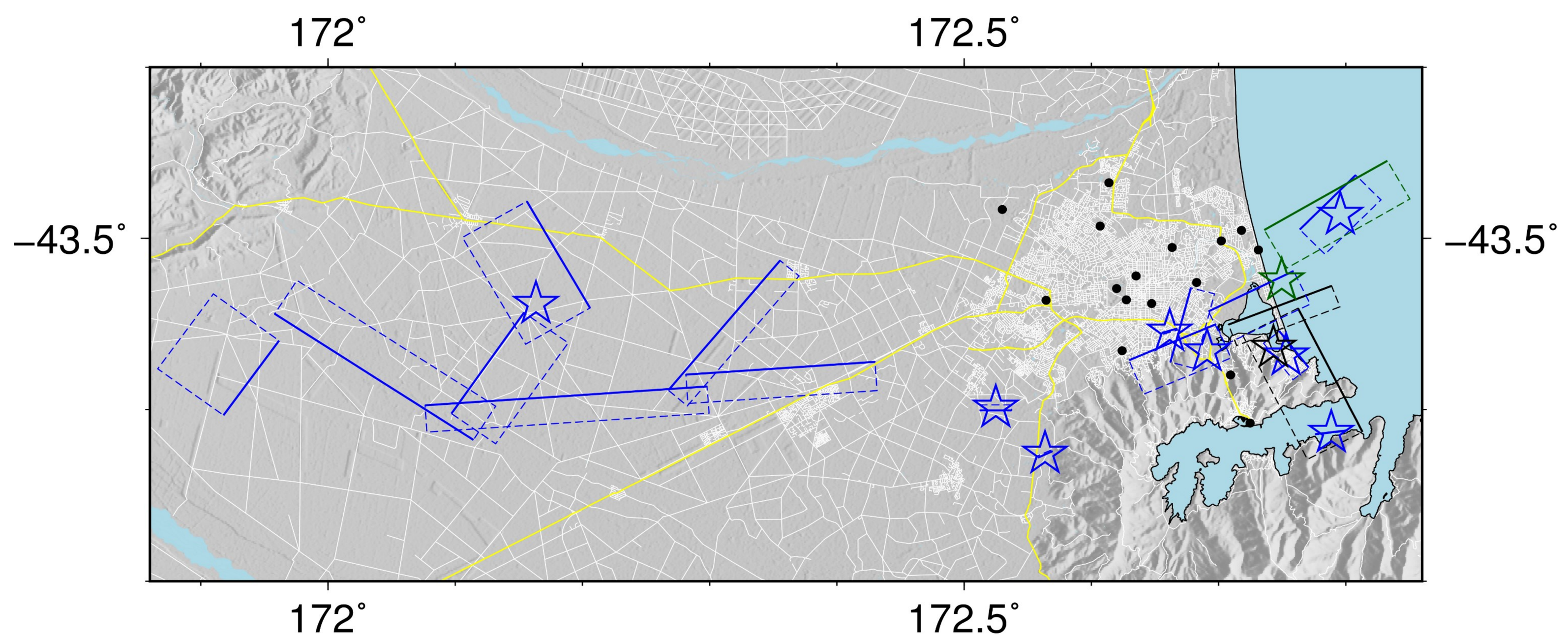

Figure 2: Earthquake rupture models for the 10 simulated earthquakes and locations of 16 strong motion stations analysed.

4. Results and Conclusions

Acceleration response spectra are compared for each ground motion at all sites, as illustrated for two examples in Figure 3. Simulations that model site response via the empirical V_{S30}-based and the wave propagation methods, and viscoelastic simulations with a minimum Vs of 500 m/s that neglect site effects are compared to observed ground motions. The observed-to-simulated residual of spectral accelerations is then computed.

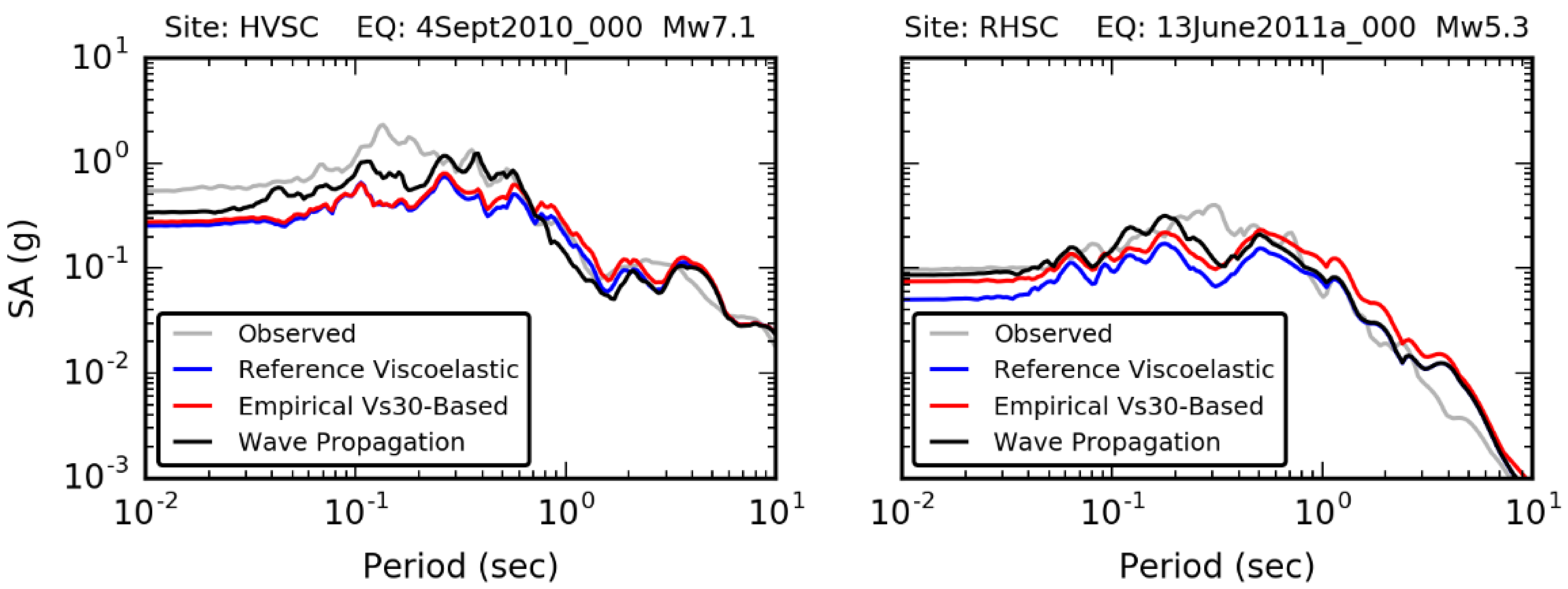

Figure 3: Comparison between observed and simulated acceleration response spectra for the empirical V_{S30}-based method, wave propagation site response analysis, and reference viscoelastic simulations.

Pseudo-Spectral Acceleration Prediction Residual

The site-specific residual is computed as the average residual across all 10 earthquakes at each site. Figure 4 plots the mean of site specific residuals for each method across all 16 sites. There are three notable observations to be made from this figure:

- Over a wide period range, consideration of site effects using both the empirical and wave propagation methods results in reduced bias (i.e., residuals closer to zero) relative to the reference viscoelastic simulations which ignore site effects.
- The V_{S30}-based approach significantly over-amplifies the long periods and the wave propagation method performs better in this period range, suggesting that the long period component of the simulation is capturing deep site effects reasonably well and that the period range over which the empirical amplification function is truncated (see Figure 1a) needs to be revised.
- The empirical V_{S30}-based method performs slightly better than the wave propagation approach at short periods. This could be caused by over prediction of the semi-empirical high frequency component of the simulation which uses simplified physics, or perhaps the 1D site response analysis doesn't properly attenuate high frequencies which leads to excessive site amplification.

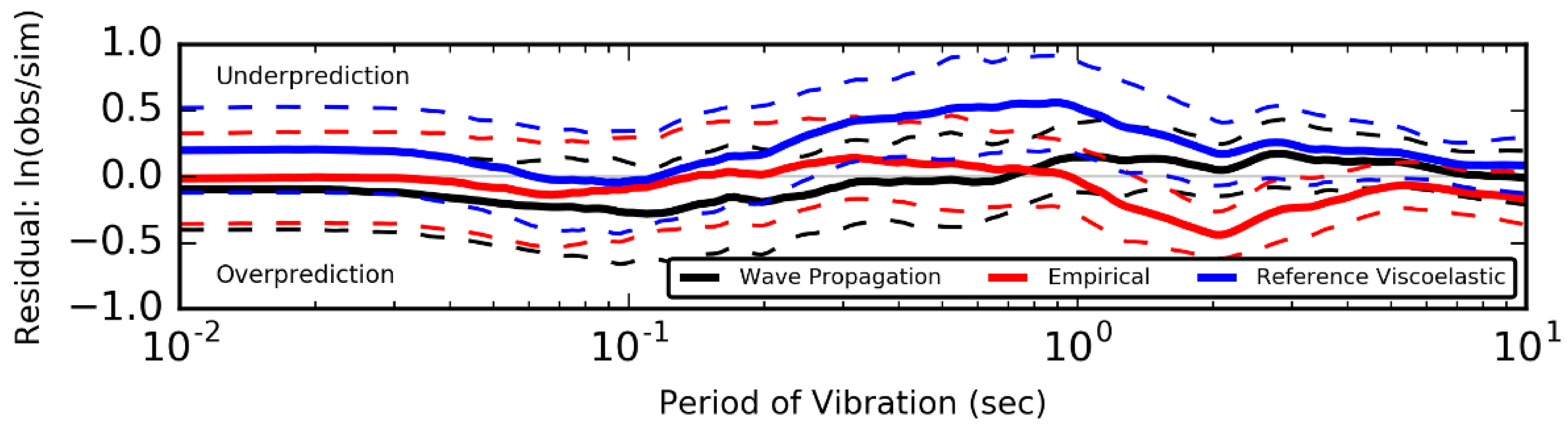

Figure 4: Mean of site-specific residuals for 10 earthquakes at 16 strong motion stations in Christchurch for simulations that model nonlinear site effects via wave propagation site response and empirical V_{S30}-based site amplification factors, and simulations that neglect site effects (i.e., reference viscoelastic condition).